Robust Multivariable Flutter Suppression for the Benchmark Active Control Technology (BACT) Wind-Tunnel Model

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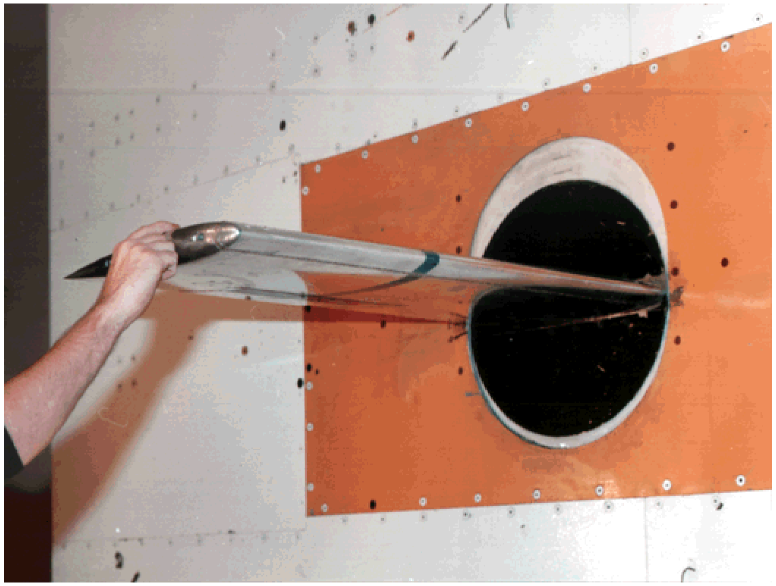
Dynamics and Control Branch

LaRC Technical Forum
January 15, 1996

Outline



- **BACT Overview**
  - **Program**
  - **Wind-Tunnel Model**
- **Design Model**
- **Control Design and Test**
  - **Flutter Suppression with Spoilers**
  - **Robust Multivariable Designs**
- **Controller Performance Evaluation (CPE)**
- **Concluding Remarks**

BACT Program Overview

- **Benchmark Aeroelastic Models Program**
  - **study physics of aeroelastic phenomena**
    - » **classical transonic flutter "bucket"**
    - » **shock induced instabilities**
    - » **dynamic vortex-structure interaction**
  - **data to validate steady and unsteady aero codes**
  - **active control of aeroelastic systems**
- **Benchmark Active Control Technology (BACT)**
  - **high quality unsteady aero data near flutter**
  - **active flutter suppression**
    - » **innovative control concepts - spoilers and multiple effectors**
    - » **innovative design methods - H_∞, μ-synthesis, neural nets**
  - **validate on-line controller performance evaluation tool**

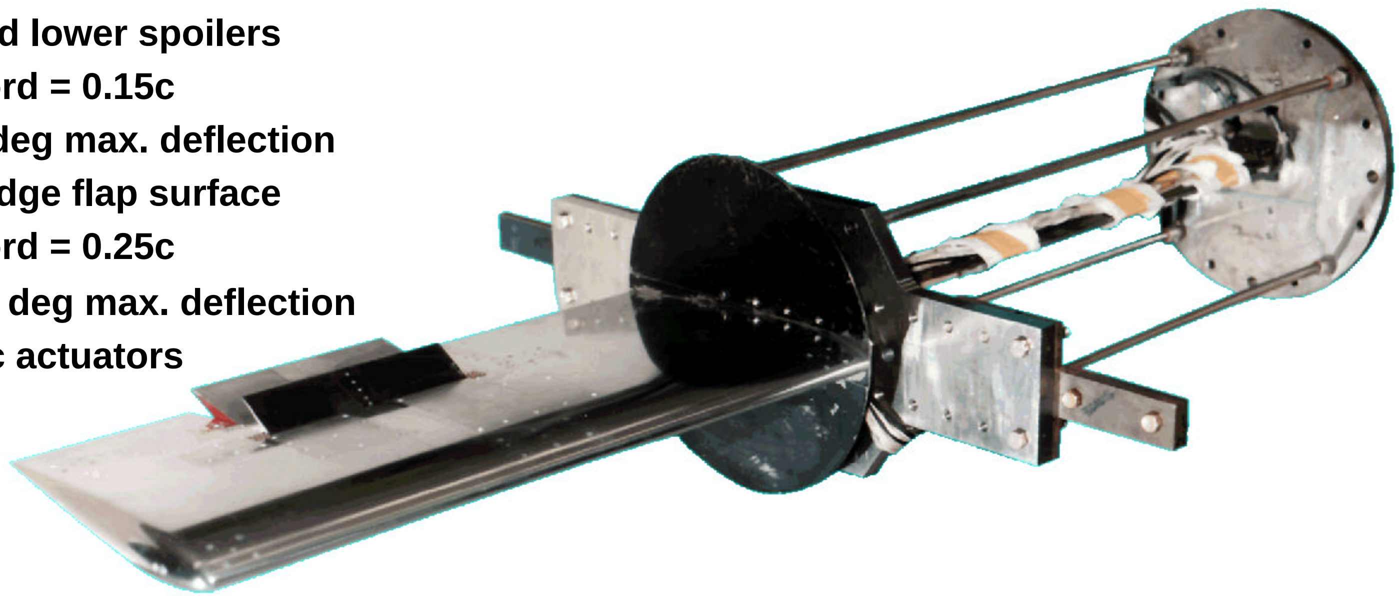
BACT Project Team

- **Diverse Interdisciplinary Team**
  - **SD, FDCD, Guest Investigators (LaRC, ARC, MDA, Orbital Research)**
  - **Aerodynamics, Aeroelasticity, Dynamics and Control, Fabrication and Calibration, Parameter Identification, Information Systems**

- **Core Team**
  - **Rob Scott (Team Leader)**
  - **Robert Bennett**
  - **Sheri Hoadley**
  - **Robert Sleeper**
  - **Marty Waszak**
  - **Carol Wieseman**

BACT System Overview

- **Pitch and Plunge Apparatus (PAPA)**
  - **2-DOF : pitch and plunge**
  - **5-6 deg max. rotation**
  - **1.5 inch max. deflection**
- **Wind-Tunnel Model**
  - **rigid NACA 0012 airfoil**
  - **AR = 2 (c = 16 in., b = 32 in.)**
- **Control Surfaces**
  - **span = 0.3b, centered at 0.6b**
  - **upper and lower spoilers**
    - **chord = 0.15c**
    - **45 deg max. deflection**
  - **trailing edge flap surface**
    - **chord = 0.25c**
    - **±15 deg max. deflection**
  - **hydraulic actuators**
- **Instrumentation**
  - **4 accelerometers in corners of wing**
  - **pitch angle sensors**
  - **70 pressure transducers**
    - **58 @ 0.6b (incl. control surfaces)**
    - **17 @ 0.4b**
  - **add'l transducers on splitter plate**
  - **accels and strain gauges on PAPA**

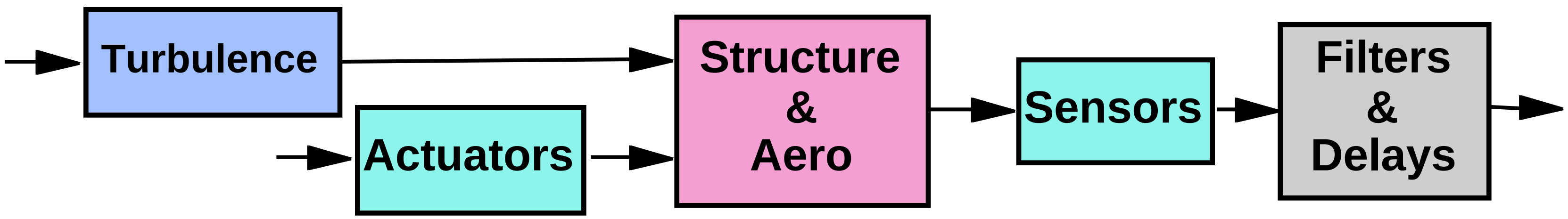


BACT Project Chronology

Tunnel Entry	Data Collected	Key Outcome
October 1993	• Steady Loads & Pressures • Unsteady Loads & Pressures • Flutter Boundary • Frequency Responses	• Control Design Model
January 1995	• SISO Flutter Suppression • SISO CPE Validation • Neural Network Gain Scheduler • Adaptive Predictive Controller • Turbulence Response	• Flutter Suppression with Spoilers • Benefit of Multivariable Control • Validated SISO CPE
February 1996		• MIMO Flutter Suppression • Validated MIMO CPE

Modeling for Flutter Suppression

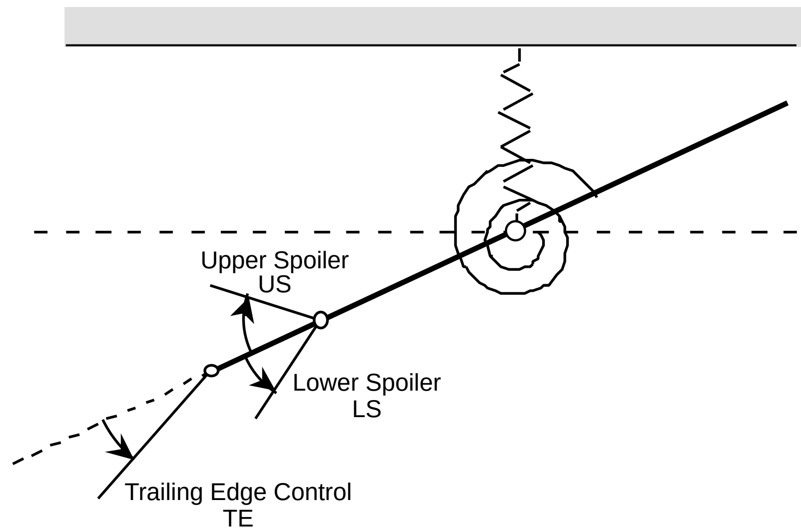
- **Model elements**
  - **structural dynamics**
  - **steady and unsteady aerodynamics (including control effects)**
  - **turbulence effects**
  - **actuators, sensors, controller effects**



- **Accurately characterize dynamic response**
  - **over flutter frequency range**
  - **wide range of Mach and dynamic pressure**
  - **due to spoilers (not possible with "standard" modeling method)**
  - **characterize effects of key parameter variations**
    - » **sensitivity analysis**
    - » **uncertainty models**

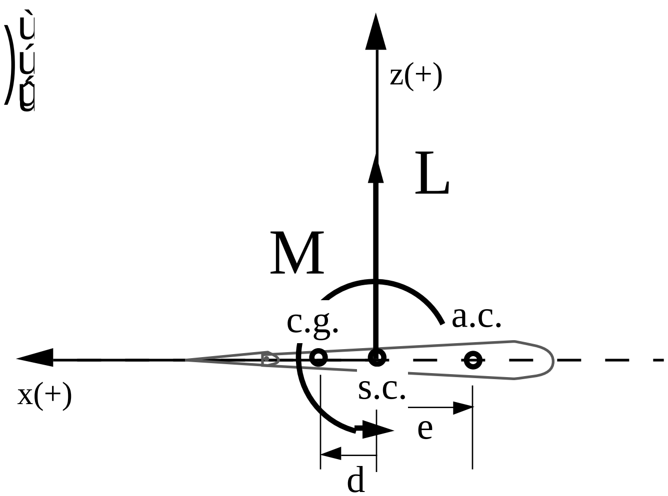
Modeling Approach

- **Idealized structure**
  - **2-DOF : pitch and plunge**
  - **linear**
- **Aerodynamics**
  - **linear**
  - **no lag terms,** ω**c/2U**$_0$ $= 0.044$



$$\alpha(t) = \theta_T + \theta(t) + \frac{\dot{h}(t)}{U_0} + \frac{\ell(x)\dot{\theta}(t)}{U_0} - \frac{w_g(t)}{U_0}$$

$$L = \bar{q}S\left[C_{L_0} + C_{L_\alpha}\alpha + C_{L_\delta}\delta + \frac{\bar{c}}{2U_0}\left(C_{L_{\dot{\alpha}}}\dot{\alpha} + C_{L_q}q + C_{L_{\dot{\delta}}}\dot{\delta}\right)\right]$$



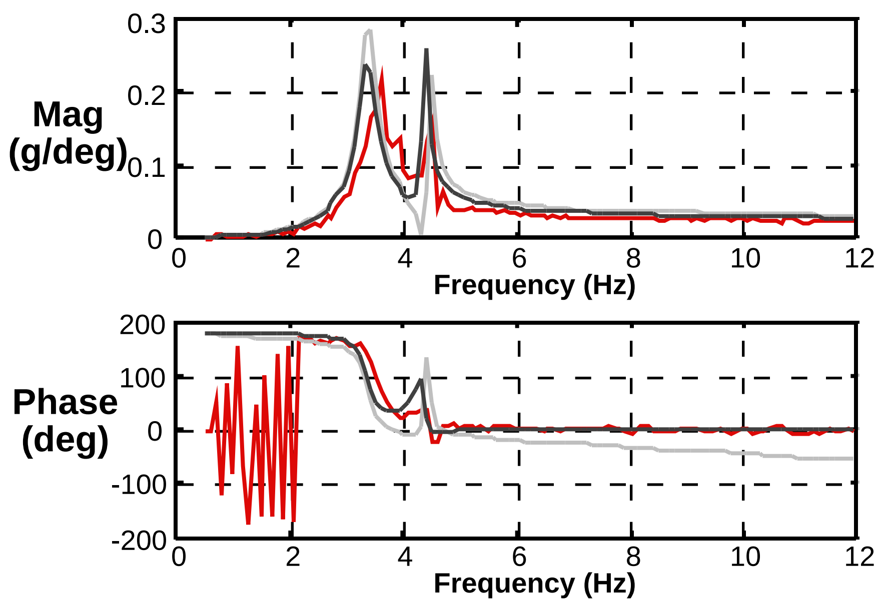
- **EOM's**
  - **Lagrange's equations**
  - **Principle of virtual work**
  - **Experimental data in numerical model**

Model Accuracy - Frequency Response

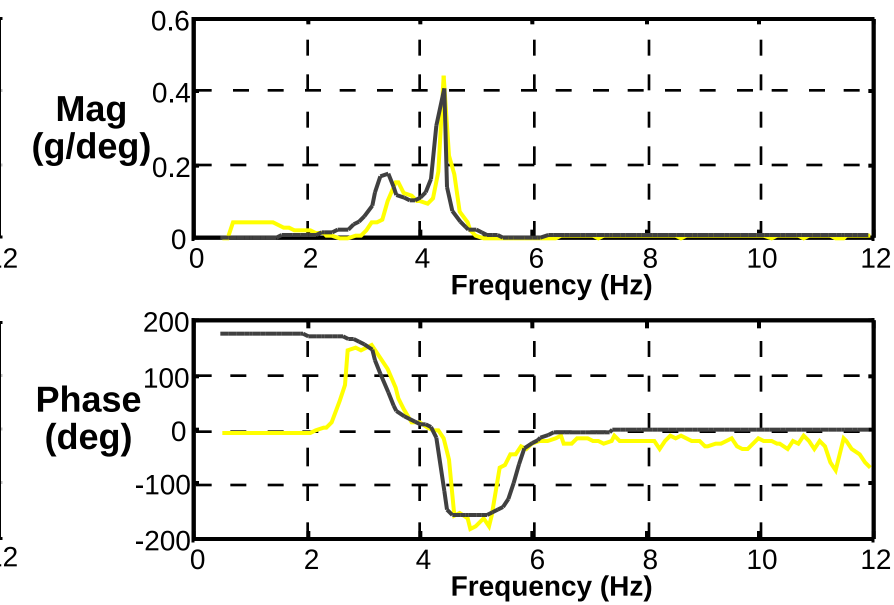
- **Subcritical Condition : M=0.77, q=125 psf**
- **Trailing edge inboard acceleration (g's)**

experiment
model
ISAC

Trailing Edge Flap

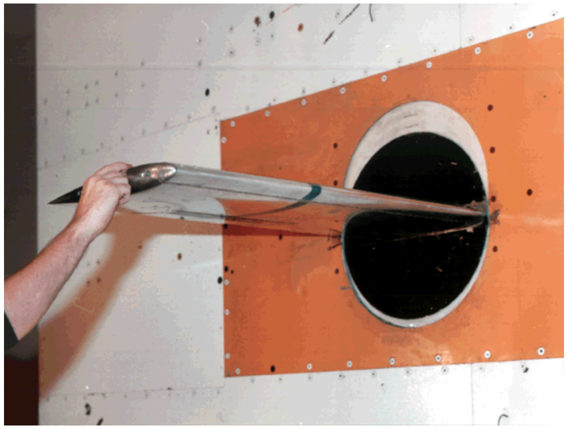


Upper Spoiler



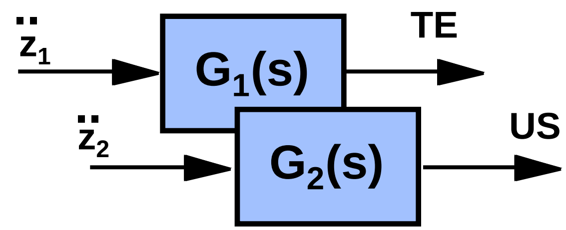
Modeling Summary

- **Complete simulation model for control system design**
  - **Accuracy demonstrated**
  - **Implemented in MATLAB™/SIMULINK™**
  - **Fully Documented**
- **Used in design of several control laws**
  - **Classical**
  - **H∞ and μ-Synthesis**
  - **Generalized Predictive Control**
  - **Neural Net Control**
- **Multiple Internal and External Customers**
  - **Dynamics and Control Branch, Aeroelasticity Branch**
  - **McDonnell-Douglas Aerospace**
  - **VPI, AFIT**
  - **U of Minnesota, Duke, ODU, U of Missouri, U of Naples**

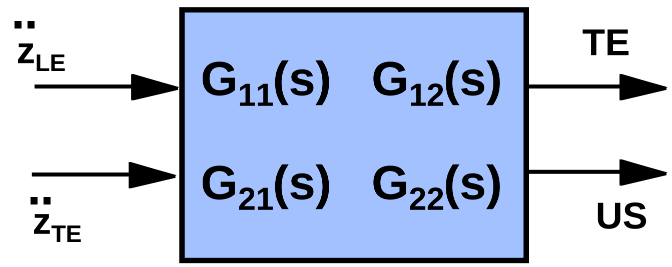


Flutter Suppression Control Laws

- **Design Objectives**
  - **Stability Over Entire Operating Range**
  - **Maintain Stability Subject to Modeling Errors**
  - **Acceptable Control Activity**
- **Traditionally Designed SISO Controllers**
  - **Demonstrate Flutter Suppression Using *Spoilers***
  - **Develop Performance Specifications**
  - **Coupled SISO Controllers**

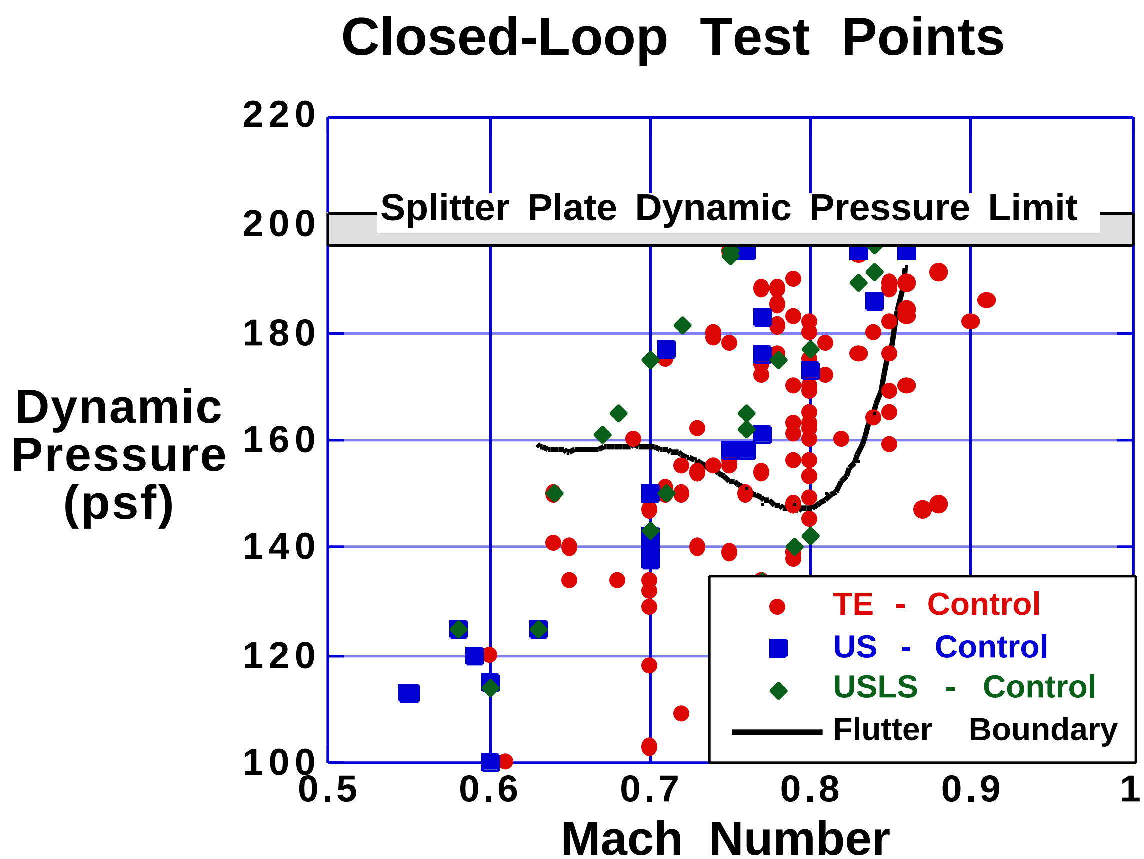


- **Robust MIMO Controllers**
  - **Demonstrate Multivariable Flutter Suppression**
  - **Evaluate Enhanced Robustness Properties**



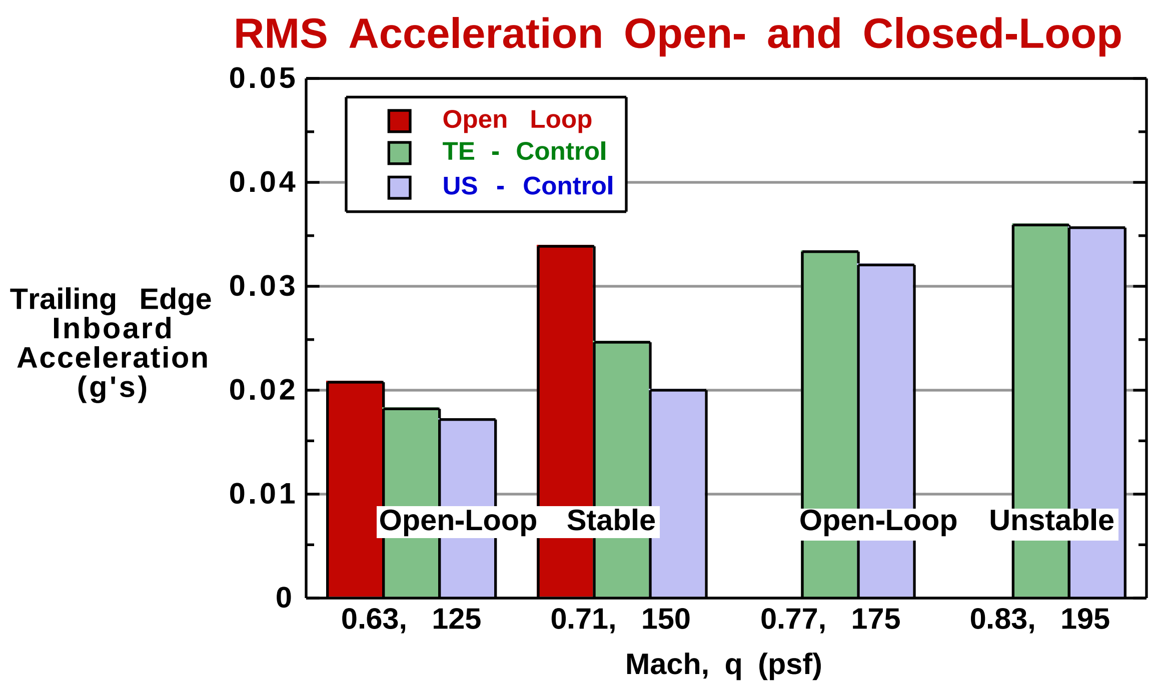
SISO Controller Summary

- **Stabilized transonic flutter instability**
- **Operated over wide range of conditions**



SISO Controller Performance Summary

- **Reduced acceleration levels over entire operating range**
  - **Gust Load Alleviation for open-loop stable conditions**
  - **Flutter Suppression when open-loop unstable**



- **Enhanced performance with coupled controllers**

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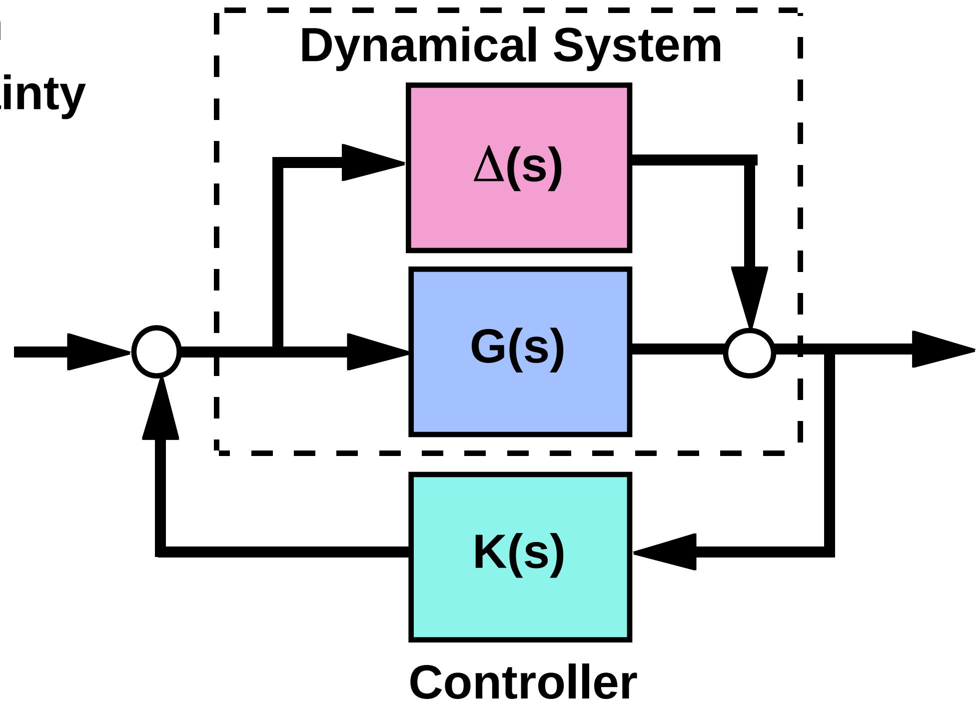
MIMO Controller Design Methods

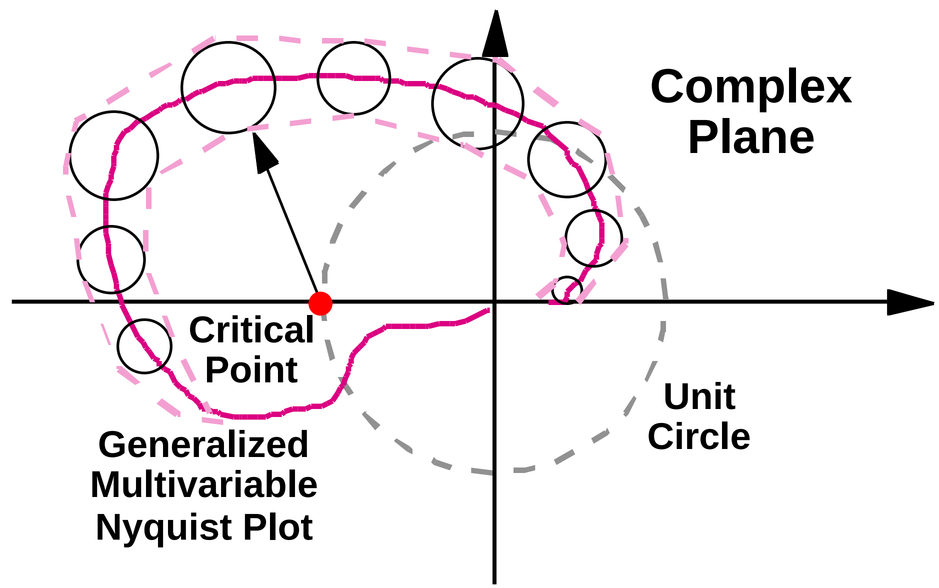
- **Robustness**
  - **Maintain Stability and Performance Subject to Model Variation**
  - **Variations Include**
    - » **Operating Condition**
    - » **Model Error/Uncertainty**



- **H∞ Control**
  - **Robust Stability**
  - **Nominal Performance**
- **μ-Synthesis**
  - **Robust Stability**
  - **Robust Performance**
  - **Structured Uncertainty**

Basis for MIMO Design Methods

- **Stability margins characterized by generalized Nyquist diagram**
- **Uncertainty characterized by “fuzziness” of Nyquist contour**
- **Select controller to maximize distance from critical point to Nyquist contour**
- **Satisfy performance constraints**



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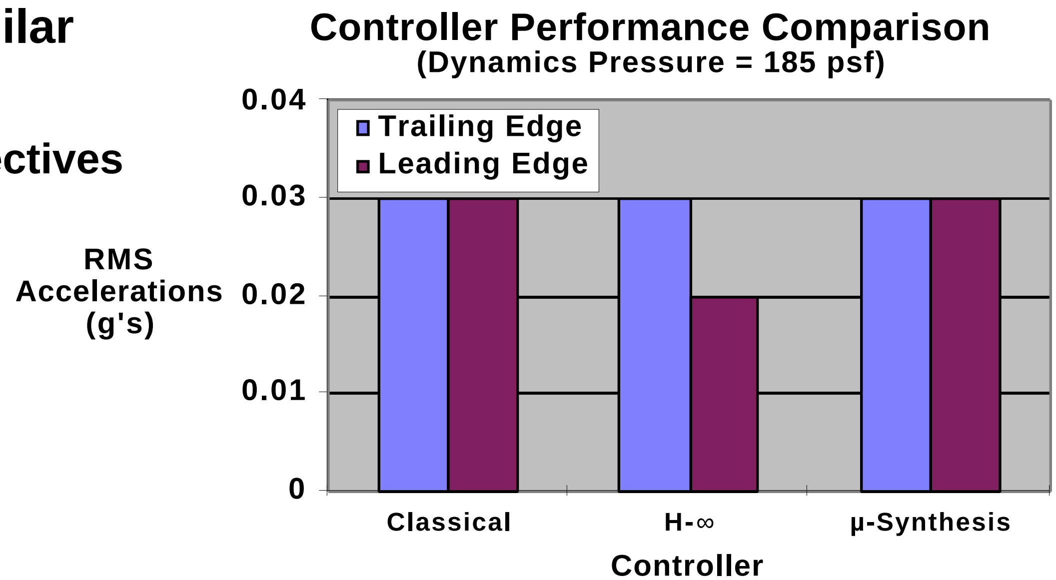
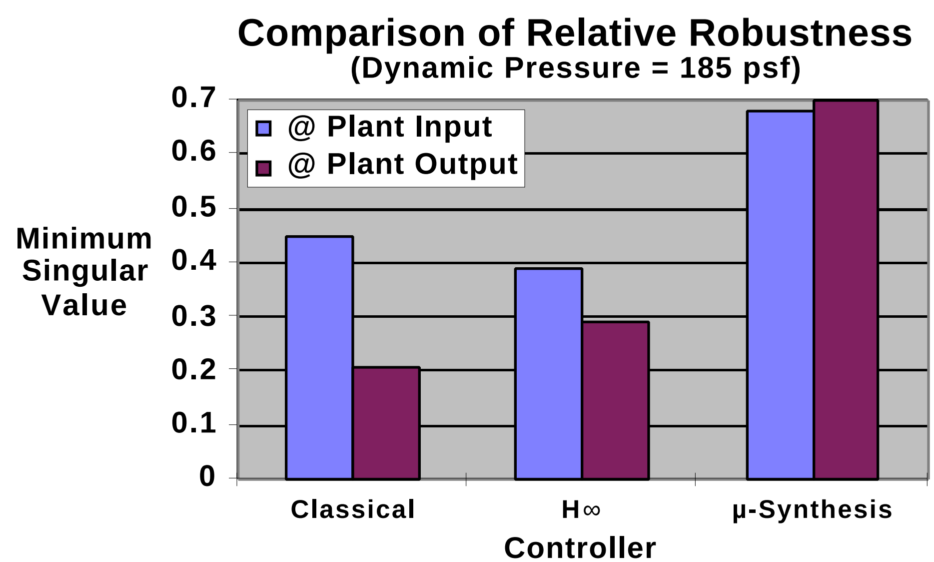
MIMO Controller Summary

- **Nominal performance similar for all MIMO controllers**
  - **similar performance objectives**
  - **actuator deadzone**



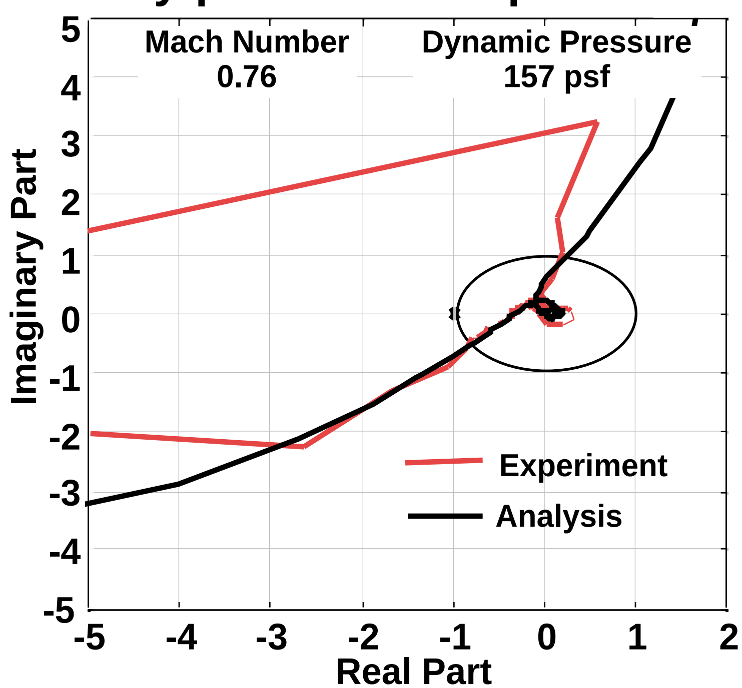
- **Better robustness for μ-Synthesis controllers**
  - **larger stability margins than classical designs**
  - **more uniform margins (i.e., at plant input and output)**



Controller Performance Evaluation

- **On-line, Near Real Time Stability Assessment**
  - **Open-Loop: Determines if controller will destabilize system**
  - **Closed-Loop: Determines stability margin for controller**
- **Greatly Enhances Safety of Active Control Testing**
  - **Less chance of damage to model and wind-tunnel**
  - **Less chance of equipment failure due to "heavy wear"**
- **Enhances Productivity**
  - **Less time required to verify controller performance**
  - **Reduces stress and anxiety**
- **Validation Process**
  - **Design controllers to vary gain and phase**
  - **Compare stability margins while varying gain & phase in various channels**

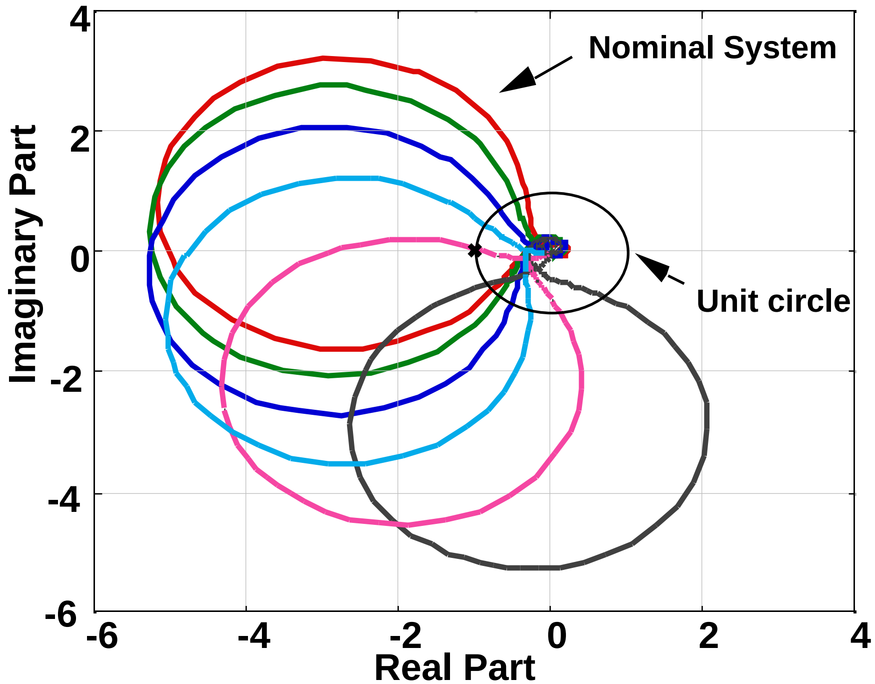
Nyquist Plot Comparison



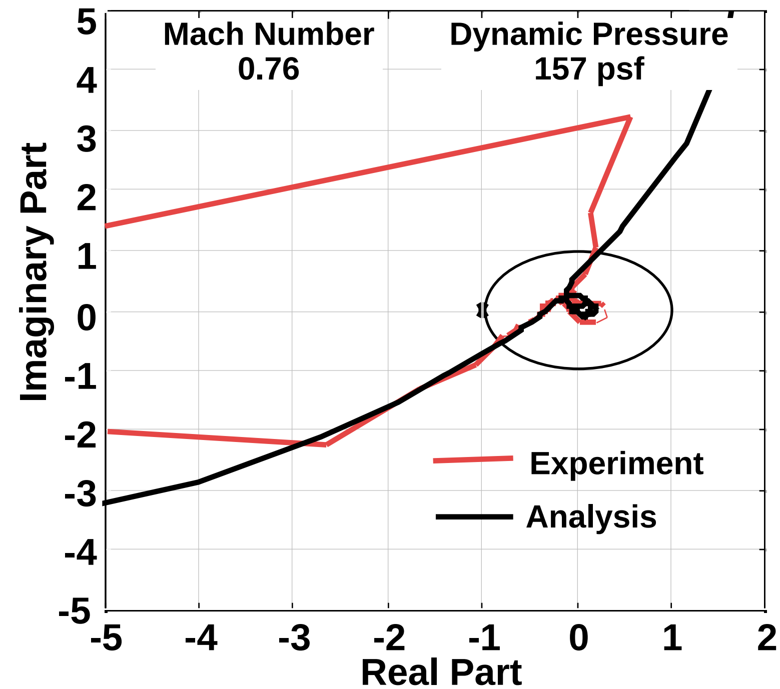
CPE Tool Validation

- **Demonstrated Accuracy of SISO Margins**
- **Demonstrated Convervatism of MIMO Margins**

Nyquist Plots for Increasing Phase Lead

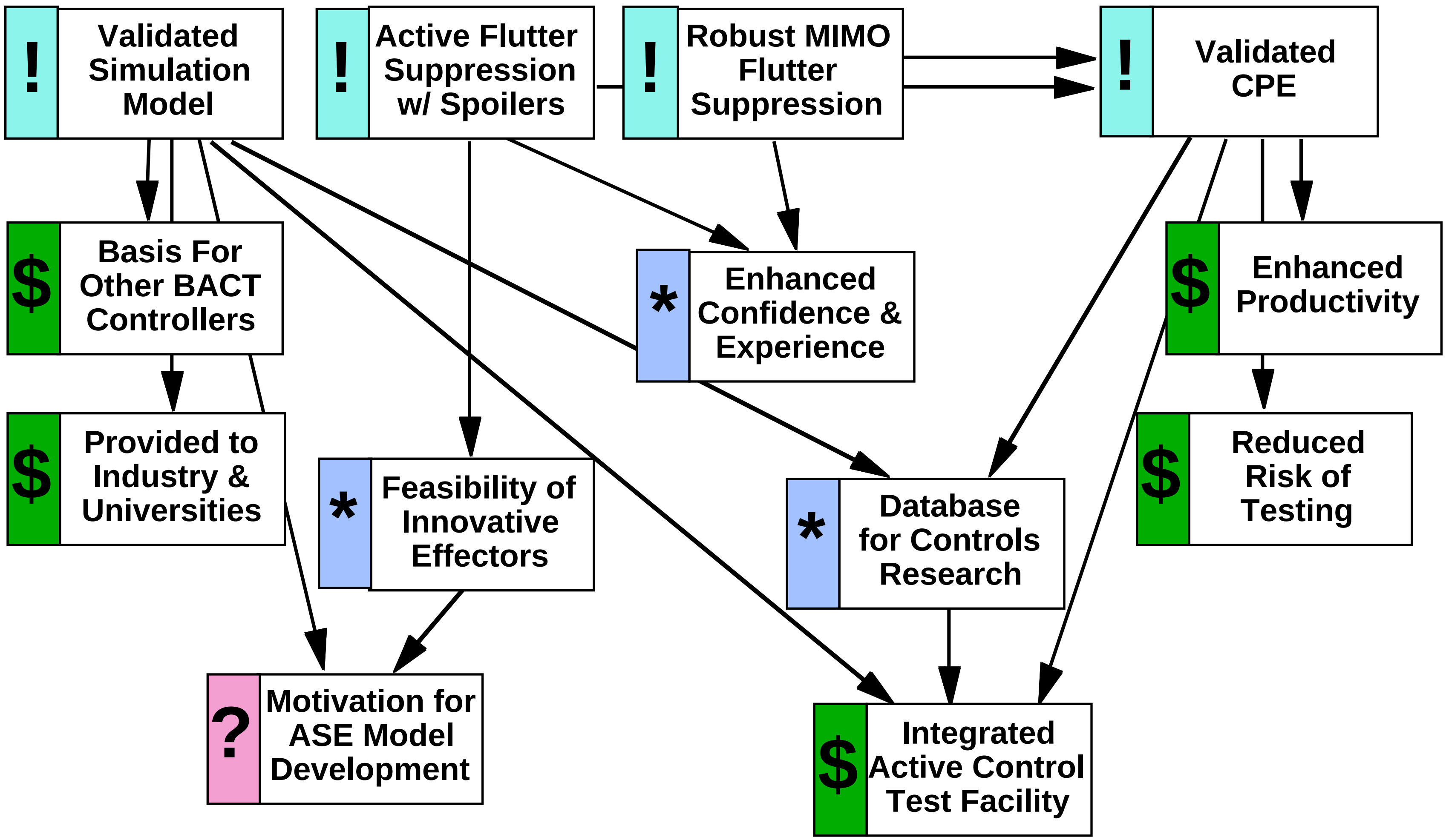


Nyquist Plot Comparison



- **CPE Enhances *Safety* and *Productivity***

Key Accomplishments



Technical Accomplishments

- **Spoilers for Flutter Suppression**
  - **Representative of "Innovative Control Effectors"**
  - **Additional Design Freedom**
  - **Enhanced Redundancy**
- **Robust Multivariable Flutter Suppression**
  - **One of the First Demonstrations**
  - **Enhanced Performance (over SISO designs)**
  - **Enhanced Robustness**
  - **Identified Deficiencies in Methods**
    - » **Inability to Accomodate Practical Needs (e.g. Washout)**
    - » **Sensitivity to Performance Specifications**
    - » **Numerical Algorithms and Convergence Issues**
- **Validated CPE Tool for Active Control Testing**
  - **Enhanced Productivity**
  - **Reduced Risk of Damage to Model and/or Tunnel**

Additional Accomplishments

- **Fully Documented Simulation Model**
  - **highly valued for research and education uses**
    - » **LaRC, ARC**
    - » **McDonnell-Douglas Aerospace**
    - » **VPI, AFIT**
    - » **U of Minnesota, Duke, ODU, U of Missouri, U of Naples**
  - **unique capability of LaRC**
- **Benchmark Active Control Database**
  - **Basis for Comparing Other Innovative Control Designs**
  - **Basis for Improving Analytical Modeling Methods**
    (e.g., System Identification of Uncertainty Models)
- **Additional Experience/Confidence with Active Flutter Control**
- **Safe and Reliable Test Facility**
  - **multiple recovery mechanisms**
    (controller reversion, "snubber," and by-pass valves)
  - **built and maintained in-house**

Concluding Remarks

- **Effective Leveraging of LaRC's Strengths**
  - **Unique combination of LaRC Resources**
    - » **Multiple Disciplines: Structures, Aerodynamics, and Controls**
    - » **TDT Wind-Tunnel and Fabrication Facilities**
  - **Aeronautics Base Funding**
    - » **Less rigid schedule (decision points rather than milestones)**
    - » **Freedom to exploit serendipity**
    - » **Less risk averse environment**
  - **Diverse set of products**
- **Example of Fundamental/Radical Technology Development**
  - **Combines emerging technologies with unique resources/capabilities**
  - **Exhibits significant risk but with large potential technical benefit**
  - **Establishes a basis for more focused development**
  - **Enhances an already strong competitive position**
  - **Addresses an area of potentially high future demand**